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Clearing ice-clogged shipping channels

Cover: Brash ice behind vessel in St. Marys River.

CRREL Report 80-28

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Clearing ice-clogged shipping channels

George P. Vance

December 1980

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This report investigates the feasibility of clearing ice from the shipping channel of the St. Marys River. Four basic concepts are investigated: disposal under the ice, disposal on top of the ice, slurrying, and rafting. Each technique was found to have application in limited portions of the river with the exception of disposal on top of the adjacent ice sheet, which is deemed feasible throughout the river system. Disposal onto the adjacent ice sheet will increase the free stream velocity less than 1.0 ft/s (30.5 cm/s) and raise the water level less than 1.0 ft (0.30 m). Further model and field tests are recommended to validate the findings of this report.

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PREFACE

This report was prepared by Dr. G.P. Vance, Research Engineer, Ice Engineering Research Branch, Experimental Engineering Division, U.S. Army Cold Regions Research and Engineering Laboratory in response to U.S. Coast Guard MIPR Z20099-8-85300-3 B.

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CLEARING ICE-CLOGGED SHIPPING CHANNELS

George P. Vance

INTRODUCTION

The need for keeping the ice prone rivers and lakes used for commercial shipping open year-round or near year-round brings with it many problems, not the least of which is disposing of the ice that is found in the shipping channels. This ice may appear in several different forms, such as sheet ice, frazil ice, brash ice, refrozen brash ice and mush or a combination of the above.

In many locations this ice has a tendency to accumulate to a point where the channel becomes so clogged it is virtually impossible for any vessel to negotiate it. Conventional icebreakers have not been able to relieve this problem. Once they leave the area, the channel quickly becomes blocked with ice again. These locations are usually areas of low flow or unusual hydraulic configuration such as a narrowing of the river or a sharp bend.

In order to remove this impediment to navigation, the U.S. Coast Guard is considering physical removal of the ice. Several concepts for removing ice were discussed by Mellor et al. (1978), but the actual impact of such removal was not addressed in detail. The object of this report is to examine in greater detail the hydraulic and environmental effects of such a removal process. The environmental investigations are limited to physical effects and do not include biological and botanical effects.

In order to limit the scope of the investigation to that of a realistic undertaking, this study will concentrate on four removal techniques: displacement, ejection, slurrying and rafting in one geographical area, the St. Marys River. The amount of ice and ice/water mixture that has to be moved, the distance it has to be moved, and the locations to which it will have to be moved will also be considered.

THE ENVIRONMENT

There are four areas in the St. Marys River that have been subject to the accumulation of brash/frazil ice (Remus 1979):

- Little Rapids Cut
- Middle Neebish and Munuscong Channels
- Lime Island Channel
- De Tour Passage

The general location of these areas is shown in Figure 1. It can be seen that in the first two of these areas, the river is at its narrowest. The passage through Middle Neebish and Munuscong Channel is particularly tortuous, with several sharp turns. Each area is subject to the accumulation of ice. The channel width at Middle Neebish is less than 200 m (656 ft) and at Little Rapids Cut it is not much greater than that. The average depth of the channels in these two areas is 8.5 m (27.8 ft).

Details of the environment including daily temperatures and ice thickness in the areas under consideration are given in Mellor et al. (1978) and Wuebben et al. (1978). This information will be useful for determining the ice growth under static and dynamic conditions in the ship channel. A photographic review of the conditions in the St. Marys during the winter of 1979 was presented by Vance (1979). It will be useful to review this photographic documentation for it provides considerable insight into the growth, distribution and breakup of the ice in the St. Marys during an ice season.

The photographs for the week of 5 January depict the conditions a week or two after the initiation of ice

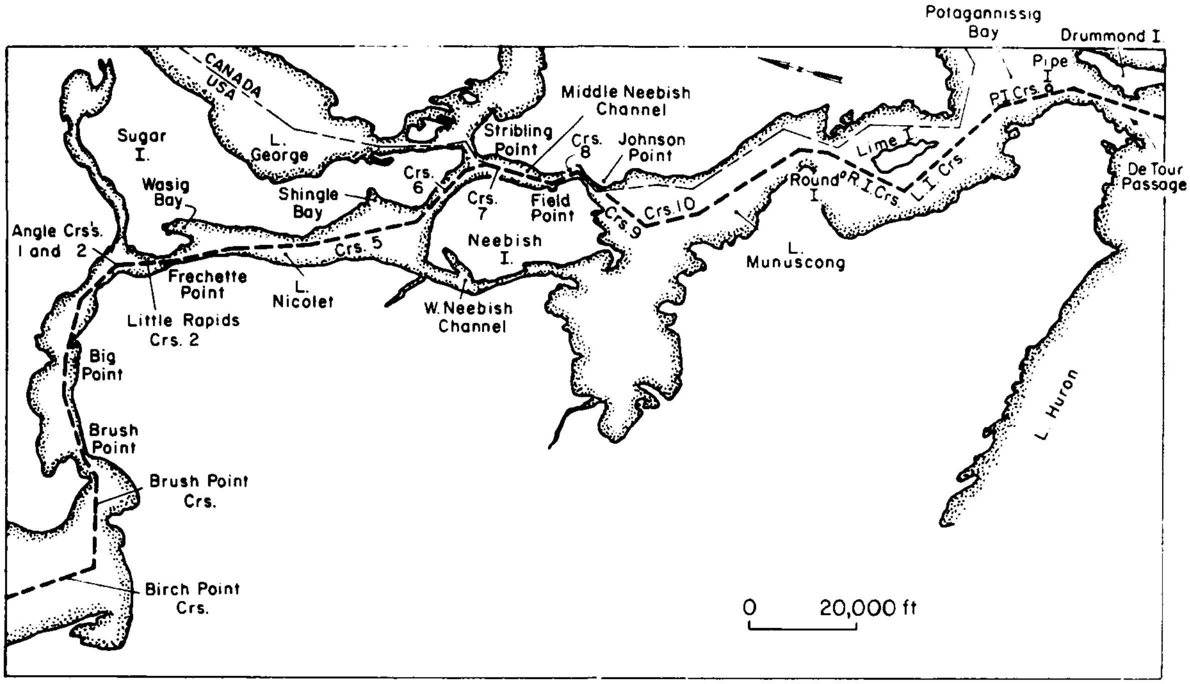


Figure 1. The St. Marys River (general location map).

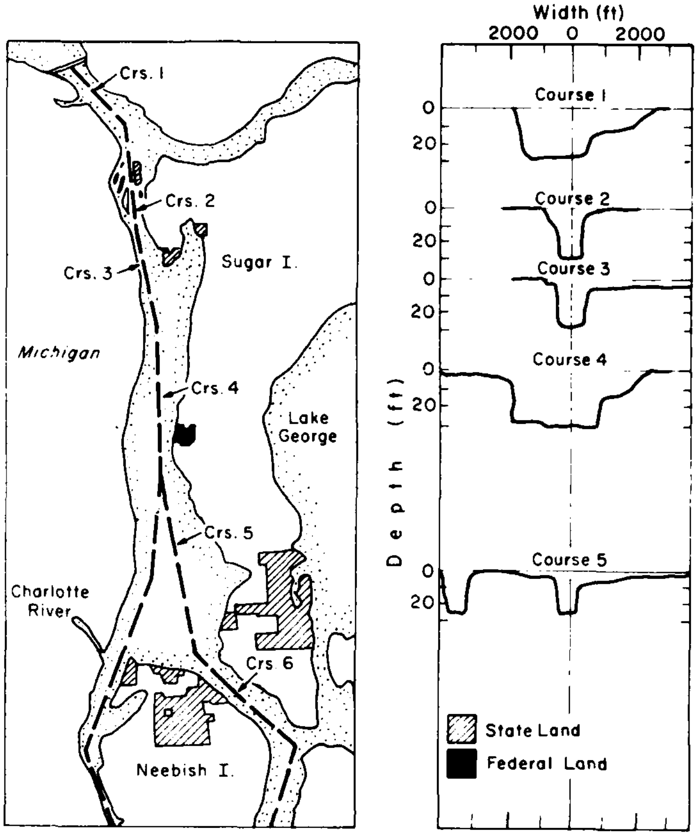
growth. They indicate that Little Rapids Cut (see Fig. 1) is open and clear to below Island Number 4. One can also see the brash ice starting to build up at Stribling Point and in the Middle Neebish Channel area, particularly at the sharp turns. There appears to be no particular buildup in Lake Munuscong, although plate ice is clearly evident. The Lime Channel is clear. There appears to be considerable brash ice in the area of the De Tour Village ferry crossing. The area from the crossing out past De Tour Light is fairly clear.

On 10 January, the brash ice is beginning to back up in Little Rapids Cut and is approximately at the south tip of Island Number 4. Courses 2 and 3 are beginning to fill with brash ice. Middle Neebish Channel is completely full of brash. The ice sheet is stabilizing in Lake Munuscong and around Pipe Island. Of considerable interest in these photographs is the stable ice sheet just upstream of the De Tour-Drummond Island ferry crossing. With the stable ice sheet, the ferry crossing and channel from the town of De Tour to De Tour Light is relatively brash-free.

By 15 January ice conditions have become considerably worse. The brash ice has now backed up in Little Rapids Cut to the midpoint of Island Number 1. Several vessels moving through the anchorage area have caused large floes to move into the channel at courses 3 and 4. The brash in Middle Neebish Channel continues to build up with little or no relief. Lake Munuscong and the Lime Island Channels have undergone little change. The Pipe Island Channel is relatively open due to the breaking away of large pieces of shore ice. These floes have caused considerable amounts of brash and floe ice to collect in the ferry crossing area as far out as De Tour Light. This is a considerable change from the 10 January conditions. It would appear that some form of ice control structure, i.e. an ice boom or ice anchor, could mitigate or eliminate the instability of the shore ice upstream of the De Tour Village ferry crossing, thereby decreasing the amount of brash in the channel.

By 28 January the ice has just about reached its maximum coverage. The approach channel to the locks at Brush Point is completely filled with ice. Little Rapids Cut is filled with brash ice, with only the ferry crossing being relatively ice-free. It should be noted that the ice boom upstream of the ferry crossing has kept the shore-fast ice in place. Courses 2 and 3 and all of Lake Nicolet are filled with ice, as is Middle Neebish Channel. Lake Munuscong and Lime Island Channel have stabilized and also are full of ice. Surprisingly, the Pipe Island Channel is clear from the ferry crossing to De Tour Light.

By 9 February Little Rapids Cut is full of ice to the Sugar Island ferry crossing. The remaining portion of the river is full of sheet ice and brash with the exception of that section from Pipe Island to De Tour Light. It is interesting to note that the ice sheet is now reattached to the shore upstream of the ferry crossing at De Tour. A thin ice sheet is now moving into the De Tour Light area from Lake Huron.



a. Courses 1 through 5.

Figure 2. The St. Marys River system.

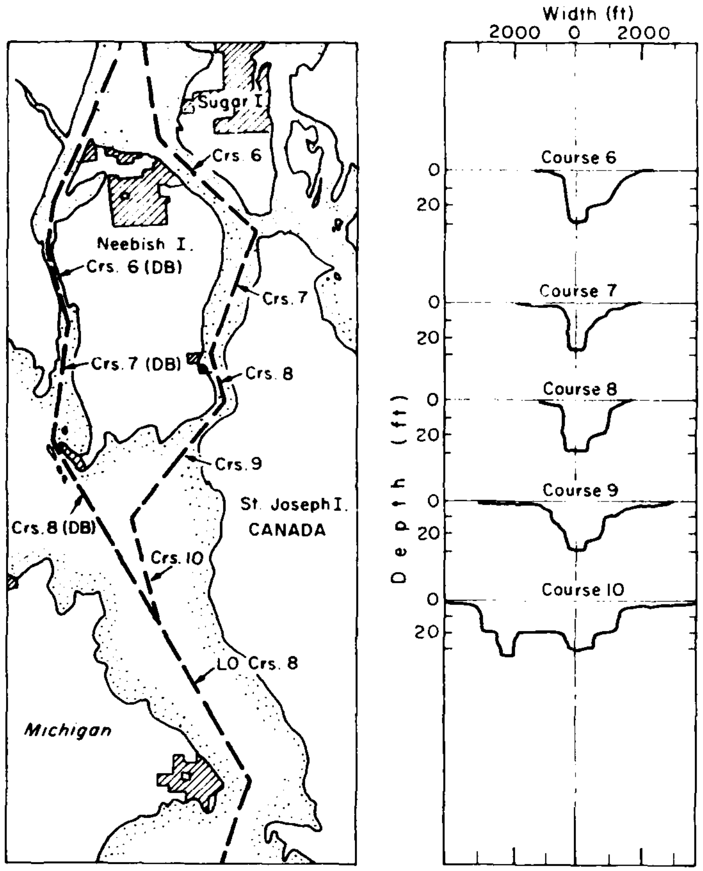
By 17 February the ice has reached its maximum coverage. Little Rapids Cut is completely full, with only a small open area at the ferry crossing. The remainder of the system through De Tour Light is full of ice.

This situation remains essentially the same until early March when melt and breakup are initiated. Unfortunately, no flights were made on 3 March and 10 March; however, the 17 March photographs indicate the channel at Big Point is starting to loosen up. There is residual brash in the channels throughout the system, but it is evident that the ice is not as closely compacted as it was during February. In fact, the channel is clear from Pipe Island to De Tour Light. This is a good indication that the brash at the lower end of the system does move into Lake Huron when it is able to.

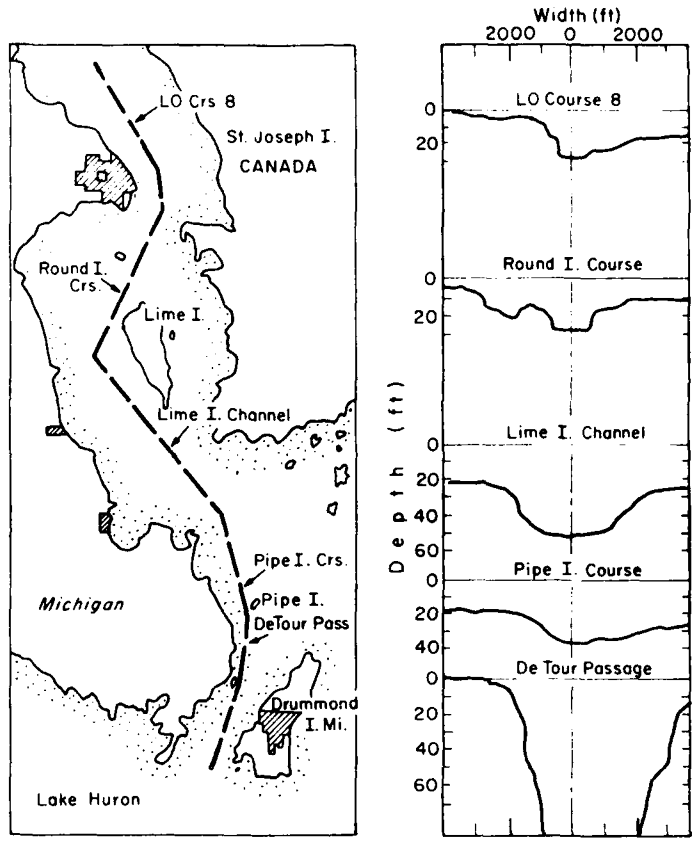
The situation is essentially unchanged on 20 March, but the brash concentration is decreasing with each day. By 3 April the system shows more areas of open water in the shipping channel. Little Rapids Cut is virtually devoid of ice. An interesting phenomenon is the appearance of open water at Stribling Point while there still is a considerable amount of loose brash in the Lake Nicolet channels. This is an indication of the insensitivity of the brash and ice floes to the low current velocities in the river, i.e. less than 2 ft/s (0.6 m/s).

Review of the ice condition photographs yields a qualitative indicator of the areas of brash buildup and the areas where a disposal technique or a combination of techniques can be utilized. The photographs also indicate that some kind of ice control structure in the De Tour Passage area just upstream of the ferry crossing might mitigate the brash problem by stabilizing the shore ice. This possibility merits further investigation.

Figures 2a-2c are plan views and cross sections of the river at various locations, along with indications of state and federally owned land along the river (Chippewa County 1973). These figures will assist in selecting potential disposal sites and in determining the feasibility of the various disposal techniques.



b. Courses 6 through 10.



c. LO course to Lake Huron.

Figure 2 (cont'd). The St. Marys River system.

ICE GROWTH AND ACCUMULATION

The ice growth rate in the various areas under consideration will not only depend on the ambient air temperature but on the temperature history of the water, the velocity regime of the river, and the extent of ship traffic in the channel.

The thermal history of the river will depend on whether there was a warm or cool fall. When the river temperature approaches 0°C, slight temperature differences, on the order of 0.05°C, will determine whether or not an ice cover forms. The first ice cover usually appears after an intense cold period, and some supercooling may occur, depending on the water velocity. The right combination of supercooling and velocity can initiate the formation of frazil ice which can significantly complicate the problem of broken brash and mush ice in the shipping channel. Ordinarily the water temperature is uniform over the full depth when the ice cover begins to form. The horizontal temperature profiles ordinarily show slightly warmer regions nearer the shore than in the center. These differences are on the order of 0.01 to 0.02°C.

The growth rate of ice in the river, both static and dynamic as well as in the shipping channel, can be related to the number of freezing degree-days that have occurred since initial ice growth. A Fahrenheit freezing degree-day D is defined by

$$D = 32°\text{F} - \frac{T_{max} - T_{min}}{2} \qquad (1)$$

where T_{max} and T_{min} are the maximum and minimum values of daily temperature in °F. This parameter is the primary variable used for calculating ice thickness in the regimes mentioned above.

For the static growth of ice, i.e. ice that is formed in areas where the velocity of the water is 0.7 ft/s (0.21 m/s) or less, the growth rate can be estimated by the empirical equation

$$h = \alpha \sqrt{\Sigma D_i} \qquad (2)$$

where h = ice thickness in inches
α = coefficient of ice growth in inches /°F$^{1/2}$ days$^{1/2}$
ΣD_i = is the summation of freezing degree-days from the initiation of ice growth.

This equation does not take into consideration any unusual environmental conditions. α itself varies from location to location and can assume a value anywhere from 0.6 to 1.0 for the units indicated above.

The freezing degree-days can be obtained from actual records in a specific location, but Figure 3 gives an indication of the accumulated freezing degree-days for the Great Lakes. For the St. Marys River a value of 1600 can be utilized, with a conservative estimate of α being equal to 0.8 (Lewis 1975). Thus the maximum ice thickness in the static reaches of the river would be 32 in. (0.813 m). This figure is at the upper end of the values reported by Vance (in press) and Voelker and Friel (1974).

At higher velocities, the ice accumulation is affected by both the velocity of the flow and the depth of the river. Several different phenomena, in addition to static growth, may act to increase the ice thickness. According to Ashton (1978), the formula governing ice

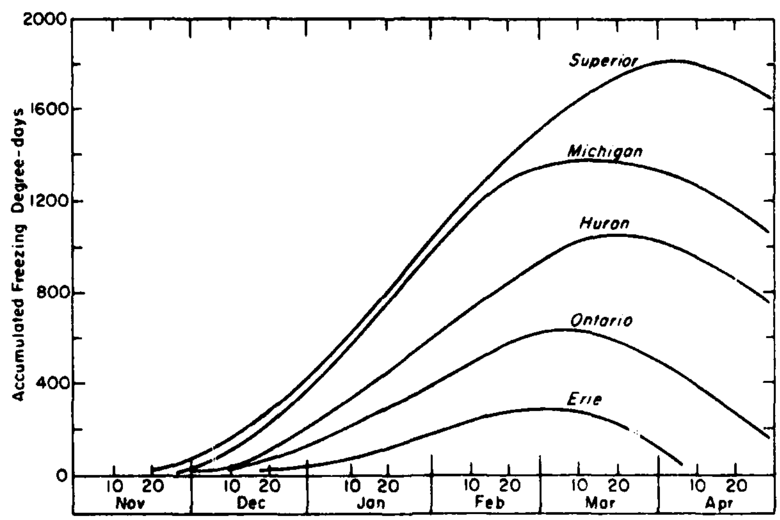


Figure 3. Freezing degree-day curves at various Great Lakes locations.

growth takes the form

$$V = \left[2gh_i\left(1 - \frac{\rho_i}{\rho_w}\right)\right]^{1/2}\left(1 - \frac{h_i}{H}\right) \tag{3}$$

where V = velocity of flow
g = acceleration of gravity
h_i = accumulated ice thickness
ρ_i and ρ_w = density of the ice and water
H = channel depth

Studies have shown that ice can accumulate to a thickness of one-third of the depth of the water under normal flow and meteorological conditions. With an average depth in the St. Marys of 27 ft (8.23 m) one could expect ice thickness of 9 ft (2.7 m). Calkins (1979) has indicated that with the presence of frazil ice in rivers, ice thickness could increase from 50 to 90% above the static growth condition. In the case of the St. Marys this could mean ice thickness of 48 in. (1.21 m) to 60.8 in. (1.54m). These figures are in agreement with the values presented by Vance (in press) and Voelker and Friel (1974). Table 1 indicates the typical flow rates and velocities measured in the St. Marys River by the Army Corps of Engineers.

The growth of ice in the shipping channel presents a difficult problem that involves not only the parameters mentioned above, but also the frequency and nature of ship passage through the channel. Michel and Berenger (1975) have developed a model of ice growth in a ship channel that takes into consideration the number of ship passages, the percentage of open water left after a ship passes through the channel, the thickness of the ice sheet before passage, and the number of freezing degree-days. They have shown that when the static growth is proportional to the square root of the accumulated freezing degree-days, the growth in a channel is a linear function of the accumulated degree-days for one ship passing per day. Since the model is complex and far too sophisticated to use here, a simplification of it can be represented by the following equation:

$$h_i = (1 - \beta)\,(h_{i-1} + \alpha\Sigma D_i^{1/2}) + \alpha\Sigma D_i^{1/2} \tag{4}$$

where β = the percentage of open water in the channel and α and ΣD_i are defined as in the static case.

With an average of 20 degree-days for each day and a value of 25% for the area of channel left open after each pass we can estimate the ice growth for any number of days, assuming one ship passage per day. Since the model shows only a slight increase in ice growth with the number of ship passages and since there are not many days when there are more than one or two ships passing, particularly if we consider a convoy of several ships as one long ship, this appears to be a good approximation of the ice growth in a ship channel. A plot of the simplified model is shown in Figure 4.

Using eq 1-3 and the findings of Calkins (1979) we can establish upper and lower bounds on the ice accumulation in the channel and at the channel sides. The results will be a function of the number of degree-days, the number of ship passages, and the water velocity in the river reach. For static growth at the sides of the channel, a reasonable bound would be from 20 to 36 in. (0.5 to 1.0 m) with a mean of 28 in. (0.7 m). The

Table 1. Velocities and flow rates in the St. Marys River.

Location	Time	Flow (ft^3/s)	velocity (ft/s)	Remarks
Little Rapids Cut	Summer 1969	52,500	2.58	1 gate open
Little Rapids Cut	Summer 1969	72,500	3.60	6 gates open
Little Rapids Cut	Winter 1976	45,300	2.46	Area reduction due to ice considered
Little Rapids Cut	Summer 1978	89,500	4.6	
Little Rapids Cut	Winter 1979	51,500	2.94	Area reduction due to ice considered
Field Point	Summer 1979	78,100	3.85	
Field Point	Summer 1978	45,600	0.85	
Field Point	Summer 1979	51,900	0.97	
Lake Munuscong	Estimated		0.25	

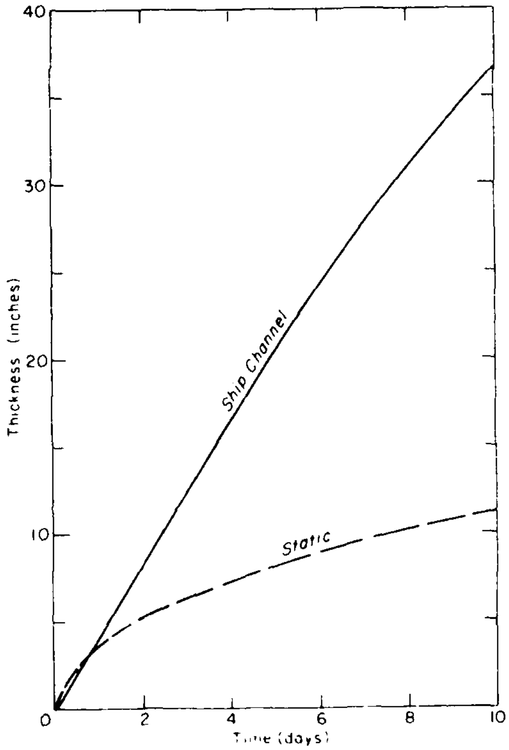


Figure 4. Ice growth in a navigable river.

bounds in the channel are a little more difficult to establish. From the pictorial history presented by Vance (1979) and from the previous discussion of conditions on the St. Marys, it is apparent that the ice conditions in the channel can vary from ice-free to ice thicknesses of 108 to 144 in. (2.75 to 3.65 m). An upper limit of 96 in. (2.44 m) has been suggested by the U.S. Coast Guard. Mellor et al. (1978) utilized a figure of 39.4 in. (1 m) for the upper limit over the total length of the river. It is evident from field measurements (Voelker and Friel 1974, Vance, in press) that these figures may well bracket the actual ice thickness. In addition, it appears that the brash ice is not of uniform thickness throughout the entire river system. Therefore, a more realistic approach would be to estimate the ice thickness for each disposal technique and each specific site.

NATURAL ICE TRANSPORT

Before the investigation of the various disposal techniques is undertaken, we must examine the conditions under which an ice slab that is deposited under an ice sheet remains there or is transported elsewhere.

The forces involved are those of buoyancy, friction, drag and dynamic lift. Figure 5 defines the dimensions and parameters involved in the calculations.

The drag force can be expressed by

$$F_D = C_D \frac{\rho_w V^2}{2} w h_s \tag{5}$$

where C_D = drag coefficient
ρ_w = density of the water
V = velocity of the water
h_s = thickness of the slab
w = width of the slab perpendicular to the flow.

C_D varies between 2.0 and 1.18 depending on the thickness to width ratios (h_s/w). It reaches a value of 1.18 when $h_s/w > 0.20$ (Hoerner 1965). A reasonable value for C_D is 1.2.

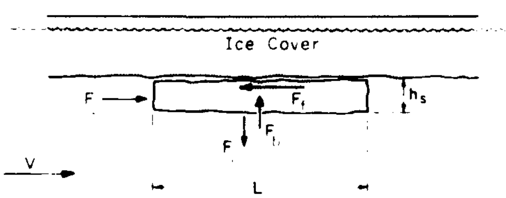


Figure 5. Definition sketch for analysis of ice slab transport (Lecourt and Voelker 1974).

The lift force can be expressed by

$$F_L = C_L \frac{\rho_w V^2}{2} L W \tag{6}$$

where C_L = lift coefficient
L = length of the slab parallel to the flow.

C_L can be taken as 0.5 for a rectangular body adjacent to a small boundary.

The friction force is defined as

$$F_F = \mu (F_B - F_L) \tag{7}$$

where μ is the friction coefficient, which, for ice on ice, can vary from 0.03 to 0.1.

The force of buoyancy is given by

$$F_B = g(\rho_w - \rho_i) h_s L W \tag{8}$$

In order to have the ice pieces float to the bottom of the ice sheet, the buoyant forces must be greater than the lift forces, i.e.

$$F_B > F_L$$

This means

$$V < 3.3 h_s^{1/2}$$

Thus, a slab 9 in. (23 cm) thick will float if V is less than 2.9 ft/s (0.88 m/s); therefore, most slabs will float to the bottom of the existing ice sheet. Higher velocities will be required to move any slab thicker than 9 in.

In order for the slab to remain in place, the friction force must be greater than the drag force (assuming no adhesion or cohesion), i.e.

$$F_F > F_D$$

$$\mu (F_B - F_L) > C_D \frac{\rho_w V^2}{2} L h_s$$

and the velocity for movement will be

$$V > \left[\frac{2 \mu g \left(1 - \frac{\rho_i}{\rho_w}\right) L}{C_D \left(1 + \frac{\mu C_L L}{C_D h_s}\right)} \right]$$

If reasonable figures for slab thickness and width are 0.5 and 1.5 ft, the velocities needed to move the ice slabs would have to be greater than 0.3 to 0.5 ft/s (0.09 to

0.15 m/s). Therefore, slabs of ice from the channel will only remain under the existing ice sheet at the side of the channel if the water velocities in this area are very low, if there is some obstruction, or if there is immediate adhesion of the slab to the ice sheet.

When the conditions permit the accumulation of ice under the ice sheet at the side of the channel, the effect of water velocity can be examined by simple application of the continuity equation:

$$V_1 A_1 = V_2 A_2 \tag{9}$$

where A_1 = channel cross-sectional area at position 1
A_2 = channel cross-sectional area at position 2

Taking a typical cross section of the channel (see Fig. 2) just south of Frechette Point we obtain a cross-sectional area of 33,600 ft^2 (3121.5 m^2) with a water velocity of approximately 2.5 ft/s (0.762 m/s). If we now place 48 in. (1.2 m) of ice from a channel 328 ft. (100 m) wide * under the ice sheet, the area A will be decreased by

$$(h_c)\,(w_c)$$

where h_c = thickness of the ice in the channel
w_c = width of the channel

or 4 x 328 = 1312 ft^2. This will increase the river velocity 0 1 ft/s (0.03 m/s), which is an insignificant change, particularly considering the simplifications (on the conservative side) made in the analysis. Even if the amount of deposited ice were tripled, the velocity increase would only amount to 0.3 ft/s (0.091 m/s), still an insignificant amount. In the worst case that can be imagined, that is if the total cross section outside the channel were completely filled with ice, the velocity at Frechette Point would increase about 1.3 ft/s (0.395 m/s) to 3.8 ft/s (1 15 m/s), not an intolerable figure and one which is sometimes reached in Little Rapids Cut at high flows.

ACCUMULATION SITES

Under-ice accumulation

From the velocities presented in Table 1 and the velocity bounds necessary to keep the ice slabs floating and moving, i.e. 0.3 ft/s < V < 3.0 ft/s, it can be seen that most slabs, under most conditions, will float under the ice sheet and move downstream until an obstruction occurs such as a turn in the channel, a decrease in depth at the side of the channel, or a decrease in the stream velocity. At this time the ice will begin to accumulate up to one-third of the river depth at the side of the channel (Ashton 1979) and back up the river.

One can obtain an indication of the amount of ice that could accumulate by considering the amount of ice cleared from the channel up until the point when it begins to accumulate at the side. For example, consider the St. Marys River from Little Rapids Cut to a point at the upstream end of Middle Neebish Channel between buoys 62 and 63. Here the channel makes a dog-leg to the east that could very well cause an accumulation of ice slabs. The nominal water depth at the side of the channel at this point is 8 ft (2.5 m); this depth extends some 1500 ft (457 m) on each side of the channel. This defines an accumulation area of some 9000 ft^2. If a channel 328 ft (100 m) wide is cleared of 4 ft (1.2 m) of ice by displacement under the existing ice sheet from Little Rapids Cut to Buoys 62 and 63, a distance of 12 miles (19 km), a volume of 8.3 x $10^7 ft^3$ would have to be accommodated. The length of river affected would be

$$L_A = \frac{L_c W_c h_c}{D_A W_A} \tag{10}$$

where L_A = the length of the accumulated ice mass
D_A = the depth of the accumulated ice
W_A = the width of the river in the accumulation area
L_c = the length of the channel
W_c = the width of the channel
h_c = the thickness of natural ice in the channel.

Using the figures above for typical river dimensions in the Little Rapids Cut to Middle Neebish Channel area, the accumulation length would be approximately 9000 ft (2743.2 m). This is a length easily accommodated by the river between buoys 62 and 63 and buoys 68 and 69. In fact, data provided by Vance (in press) indicate that the brash does accumulate at this point, compared to the Little Rapids Cut area.

Two other areas in which ice accumulation is most likely to occur are the downstream end of the Middle Neebish Channel and the downstream end of Munuscong Channel at Johnson's Point. Calculations similar to those above indicate that an accumulation length of 5200 ft. (1585 m) will be required in Neebish Channel and 3500 ft (1067 m) at Johnson's Point. These distances are equivalent to approximately one-third of the total channel length to be cleared. Therefore, although it would be feasible to allow ice from a cleared channel to accumulate at these points, the short length of the channel is a potential source of problems. It may be preferable to dispose of the

* This channel width was specified by the sponsor, and although it may be excessive for winter navigation, it will be utilized as an upper bound for the analysis undertaken in this study.

ice in another fashion in these areas.

All other areas of the St. Marys River have sufficient reach lengths and river widths to accomodate ice disposal under the existing ice sheet. The velocities expected from the Lake Munuscong reaches to De Tour Passage are low enough so that the ice would remain under the ice sheet.

The De Tour Passage velocities are high enough to clear the ice out into Lake Huron. This can readily be seen from the documentation in Vance (in press).

Accumulation on top of the ice

In order to obtain some insight into the additional quantity of ice that will have to be handled and deposited on top of the ice sheet at the channel edge if the channel is kept clear, we can refer to Figure 4 and eq 2. Equation 2 yields an average ice thickness of 32 in. (81 cm) from static growth. Figure 4 indicates that an ice thickness of some 4 to 8 in., say 6 in. on the average, can grow in an open channel every two days using an average of 20 freezing degree-days per day. If these severe conditions persist for 20 days of the ice season, an additional 120 in. of ice must be removed. Therefore, the increase in volume per unit length of river is

$$V_{remove} = (h_{remove} - h)\,W_c \qquad (11)$$

$$= \frac{120 - 32}{12}\ 328 = 2405\ \text{ft}^3/\text{ft}$$

where V = volume of ice

h = thickness of ice

The total volume of ice per unit length of the river, using an average river width of 6000 ft, is

$$V_T = h\,W_r$$

$$= \frac{32}{12}\ 6000 = 16{,}000\ \text{ft}^3/\ \text{ft}$$

where W_r = width of the river.

This produces a maximum increase of 15%, a percentage well within the bounds of the natural ice thickness variations from year to year.

If this ice is deposited on top of the existing ice sheet for a distance of 1000 ft on each side of the channel, this would increase the ice thickness at the channel edge some 1.2 ft (0.36 m). If it is assumed that isostatic equilibrium is maintained and the 1.2 ft is added to an existing 2.6 ft (which is a worst case assumption) the river cross section outside the channel would decrease about 2160 ft^2 (1.2 x 0.9 x 2000 ft). If one uses the Frechette Point cross section as an example as before, this represents a velocity increase of approximately 7% (from 2.46 to 2.63 ft/s), an inconsequential increase.

EVALUATION OF ICE DISPOSAL TECHNIQUES

General

With the basic description of the river provided earlier and the methodology for determining accumulation rates established, attention can now be focused on evaluating the various ice disposal techniques. Each technique will be evaluated, considering the bathymetry and hydrography of the St. Marys River, with the goal of keeping a channel 100 m (328 ft) wide clear enough to allow passage of one or more vessels per day.

It would be idealistic to envision any clearing device as being 100% efficient; however, it would appear feasible that a device could clear away 75 to 85% of the ice. Therefore, the ice thickness predicted by the model will be increased by 15% between clearing intervals. The thickness of the static plate ice will be determined using the parameter of freezing degree-days. The accumulation of ice in the channel will be determined using the model presented earlier, which is a function of the number of freezing degree-days and the number of ship passages per day. For this study it was assumed that an average of one ship per day would pass through the channel. It was also assumed that any ice deposited at an accumulation site or at the side of the channel will not deteriorate until spring melt and breakup.

Disposal by displacement under the remaining ice sheet

This alternative is feasible in all reaches of the river, with the exception of Middle Neebish Channel and the Munuscong Channel. In these areas the width of the river and the channel length are such that there is a strong possibility of the broken ice floating back into the channel and completely blocking it. Therefore, this method of disposal should be avoided in these areas.

The channel downstream of Johnson's Point presents no particular problem for utilizing this method of disposal. Current velocities are such that a majority of the ice will be dissipated into the wide expanses of the river system in this area. A good portion of the ice will be passed out into Lake Huron from the DeTour Passage reach. That is not to say some of the ice displaced upstream will not float back into the channel downstream; this would increase the frequency of clearing.

The use of this disposal method in the Lake Nicolet reach is marginal but feasible. The channel length in this reach is some 12 miles; there is ample depth (> 8 ft) and breadth (> 3000 ft) of river on each side of the channel, up to a depth of 4 ft (2 ft of which is already frozen in place). Therefore, a storage area of 6000 ft^2

is available. If one assumes that the vessels being used are capable of negotiating 18-20 in. of refrozen brash, the channel will have to be cleared every five days. With a 50-day ice season, the channel would have to be cleared 10 times. Therefore, approximately 3.5×10^8 ft^3 (9.8×10^6 m^3) of ice must be stored until breakup and melt. This would result in 5500 ft^3/linear ft of channel (approximately 10 miles). This is an increase in ice volume of approximately 25–30% in this reach and an increase in velocity of approximately 20% from 2.5 to 3.0 ft/s (0.76 to 0.91 m/s), which is an acceptable level. The increased volume of ice will also cause an increase in water level. If the displaced water volume is restricted to the Lake Nicolet reach, which is a conservative estimate, and if the river width varies from 9000 to 12,000 ft (2.7 to 3.6 km), we can expect a rise in water from 4 to 6 in. (10 to 15 cm). This rise is less than one-quarter of the rise and fall that has been experienced in the natural yearly water level changes (Mellor et al. 1978).

Under normal conditions, the ice cover in the Lake Nicolet reach remains in place and deteriorates with very little adverse effect. If we place 30% more ice under the existing cover with the existing velocity regimes, we can expect that same behavior to persist except for the possibility of some of the ice breaking away from the shore and accumulating at the downstream end of the reach. To what extent this will occur depends on the rapidity with which the ice deteriorates and the amount of the ice sheet which is disturbed by external factors such as vessels leaving the channel or abnormally high winds. In the event that the thickened ice sheet shows a tendency to break away at any particular location, it may be possible to keep it in place with the use of some sort of ice boom.

The size of the ice pieces that can be displaced will be a function of the mechanism used to break the ice in the first place. It has been found that the USCG icebreaker *Katmai Bay* can break plate ice into pieces from 10-15 ft in diameter to less than 1 ft in diameter. Any displacement mechanism should be designed to handle such pieces. Mellor et al. (1978) have shown that the larger the piece, the greater the resistance to displacement will be, and therefore any channel clearing device should be designed to take this fact into consideration. In addition to the size of the pieces being displaced, the local currents will have a significant effect on how far under the ice sheet the pieces will go.

In summary, it appears that the disposal method of displacement under the ice is feasible in all reaches of the St. Marys River except the Middle Neebish and Munuscong Channels. In the Lake Nicolet reach, one could expect a 0.5 ft/s increase in velocity and a 4- to 6-in. increase in water level. There may be some potential for ice accumulation at the downstream end of the reach at melt and breakup if no restraining booms are put in place. No problems related to this method are anticipated in the Lake Munuscong reach and reaches further downstream.

Disposal by ejection on top of adjacent ice cover

The ejection method of disposal can be accomplished in two fashions, that mentioned by Mellor et al. (1978) (free ejection with a water nozzle) and a second method which requires a conveyor belt that would mechanically lift the ice from the channel and convey it to the adjacent ice sheet (Waggner and Coppel 1971). Both methods will be limited to distribution on a 200- to 300-ft (60- to 100-m) portion of the unbroken ice at the sides of the channel due to power and structural considerations. There is no location at which this method can be used to deposit ejected ice on snow- or ice-covered ground.

The free ejection method utilizing a water nozzle has the inherent disadvantage that the ice would have to be chopped up before it could be jetted through a nozzle. Practical considerations would limit the diameter of the nozzle to approximately 12 in. (30 cm) (Mellor et al. 1978); this in turn would limit the size of the pieces to approximately 6 to 9 in. (15 to 23 cm). Thus, the ice must undergo comminution until the largest piece has a diameter no greater than 9 in.

In addition, if a mixture of water and ice is utilized, approximately 40% of the mixture would be water. A large percentage of this water would then settle on the existing ice sheet and freeze, thereby increasing the volume of ice deposited by almost 50%. Thus in the Lake Nicolet reach, instead of having 3.5×10^8 ft^3 of deposited ice, one would have approximately 5.2×10^8 ft^3. That volume of ice can be deposited over an area of 300 ft on each side of the channel times the length of the reach, 63,360 ft, which would yield up to an additional 14 ft of ice at the channel edge.

Even if the dynamic ice growth approached the static ice growth of say 10 in. every five days, the additional ice would amount to approximately 7 ft of ice on each side of the channel, assuming isostatic equilibrium (i.e. the ice sheet at the channel edge fails or bends until the buoyant forces are equal to the weight of the ice). This also assumes that an ice sheet broken off from the shorefast ice will not float back out into the channel. Field tests (Alger 1978) have shown that a crack parallel to the shoreline will, in itself, not cause the ice sheet to move away from the shore.

The 14-ft-thick ice would cause an increase in the water velocity of about 0.8 ft/s. The 7-ft thick ice would increase the velocity some 0.35 ft/s. Both values are acceptable velocities. The water level would rise approximately 8 to 12 in. for the 20 in. per clearing ice thickness and 4 to 6 in. for the 10 in. ice thickness.

The ejection method utilizing mechanical displacement

would have values some 50% less than those of the water ejection system, i.e. a 0.23 ft/s increase in velocity and about a 5 to 8 in. rise in water level for a 20-in. ice thickness.

In the Middle Neebish Channel and the Munuscong Channel, the river is slightly narrower, 5000 to 6000 ft compared to 9000 to 12,000 ft; therefore one can expect a 50% increase in the water level and velocity, i.e. an increase in velocity of 0.5 and 0.35 ft/s with a level rise of 18 and 12 in., respectively. In the reach beyond Munuscong Channel, the river is much wider so the velocity increases and the water level rises should be substantially less.

In summary, it appears that disposal by both free ejection with a water nozzle and mechanical ejection are feasible alternatives. Free ejection is less desirable because of the 50% increase in ice volume and the large pileup of ice at the channel edge. Both methods would leave a large buildup of ice at the channel edge for some 300 to 400 ft from the channel. Theoretically, this should not cause any significant problems; however, it may not be an easy task to convince environmentalists and local residents of this fact without some physical modeling.

Disposal by slurrying

Disposal of the brash ice through slurry pipelines adds other considerations to the possibility of disposal by ejection, these being the length of the slurry pipeline and the potential of freeze-up in the pipeline. Hanamoto et al. (1976) have indicated that using a slurry saturation of 35 to 60% ice would be possible. However, laboratory tests have indicated that a slurry concentration greater than 50% ice could cause freeze-up problems in the slurry pumping mechanism and peripheral freezing of the slurry pipeline which decreases the effective pipe diameter. The potential for freezing can be decreased by keeping the slurry concentration below 50% (i.e. 40% ice, 60% water) or by introducing some sort of pump and pipeline heating. For the sake of this study, we will assume a 40% ice concentration with no ancillary heating.

Mellor et al. (1978) have shown that a slurry system using a large diameter pipe (approximately 39 in. (1 m) in diameter and about 1000 ft (300 m) long) would be energy competitive with the other systems under consideration. Such a length would be adequate for depositing the ice on top of the existing ice sheet at the side of the channel. However, a length of almost three times that utilized by Mellor (3000 ft, 1000 m) would be required to deposit the slurry on any currently state or federally owned land. Even with a 3000-ft pipeline, deposition on river ice or snow-covered ground would only be feasible in the Middle Neebish Channel and the Munuscong Channel reaches. In these reaches approximately 4.33×10^8 ft^3 (1.226×10^7 m^3) of ice (including the transportation liquid) would be deposited over 2.0×10^7 ft^2 of government owned land (this is one-half of the land owned by the State of Michigan on Sugar Island and Neebish Island with direct access to the river). This would lead to the buildup of ice some 22 ft (6.7 m) high along the shoreline. Assuming no deterioration until melt or breakup and a slow melt season, there would be a negligible effect on the river hydraulics, however, there might be a significant effect on the shoreline erosion problem. The exact nature and magnitude of the effect is beyond the scope of this report.

If we assume that the slurry is deposited on the existing ice sheet over a distance of 1500 ft on each side of the channel and that all of the transportation fluid is frozen upon deposition, then an additional 4.5 ft (1.4 m) of ice will be deposited along the channel edge.

Using the information in Table 1 for Field Point, an increase in ice thickness of 4.5 ft will increase the velocity some 20% to 1.1 ft/s, which is an acceptable value. The increase in ice volume will also tend to cause a slight increase in the water level. Again using Field Point data, the rise in water level will be no more than 10 to 16 in.

In order to utilize the slurry system, the ice must be reduced in size so that it can fit through the slurry pump and through the slurry pipeline. The pipeline itself can accommodate solids about one-quarter to one-half the pipe diameter. However, the pump itself will require much smaller pieces. A rough estimate of the necessary ice comminution for a specially designed slurry pump would be in the area of 2-3 in. (5-7 cm). In addition, approximately 8000 ft^3 of water will be needed per linear foot of channel cleared by this method. This is about 5% of the volume available, but since the water is being deposited on the existing ice sheet, and a large percentage will refreeze along with the displaced ice and seek hydrostatic equilibrium, there should be little effect on the overall volume of water.

In summary, it appears that slurry disposal on the ice sheet at the channel edge is feasible throughout the river system. There are several areas that require more in-depth investigation such as the optimum pump and pipeline size, the maneuverability of the pipeline and the freezing problem in the pipeline.

Disposal by rafting

Disposal of channel ice by rafting or flushing in the St. Marys River will be a difficult task due to the shallow depths of the river in the areas where such techniques are required. Wasig Bay at the lower end of Little Rapids Cut would be a convenient place to store the rafted ice; however, the water depth in this area is limited to 4–5 ft (1.2-1.5 m). The water depth in Shingle Bay at the lower

end of Lake Nicolet, another convenient rafting location, is only 3-4 ft (1.0-1.2 m). There are no convenient locations in Middle Neebish Channel and Munuscong Channel that are capable of accommodating the volume of ice (approximately 500 ft^3/ft of channel for the 50-day season) that would have to be stored until melt and breakup. Lake Munuscong and the Lime Island Channel, on the other hand, have ample depth and open area for the convenient rafting of ice. Ice from the Lake Munuscong reach of the river could easily be rafted northeast of the channel, between the channel and the Canadian border. Ice from the Lime Island Channel can easily be rafted into the lower reaches of Potagannissing Bay. Ice from De Tour Passage can be rafted into Lake Huron.

There is a possibility of using the old channel into Lake George for storage of the Middle Neebish Channel ice. However, there is considerable travel distance and an ice cover would have to be broken each rafting trip. Munuscong Channel ice would have to be rafted or flushed to the Lake Munuscong area, again a considerable distance.

Table 2 presents the average rafting distances for the various reaches of the river.

The size of the pieces/slabs to be rafted will vary from 15 ft in diameter to less than 1 ft in diameter. The task can be performed by a large plow type mechanism on the bow of a powerful tug or towboat or by towing a logging type boom; the exact design of the vehicle is beyond the scope of this report. It is evident from the pictorial study of the 1979 channel ice (Vance 1979) that natural flushing is occurring in the Lime Island Channel and De Tour Passage, however, this natural flushing can be expedited and controlled with the proper vehicle and ice control structures. The contour and bathymetry of the upper reaches of the river do not lend themselves to any natural flushing or rafting outside of the ship channel.

In summary, although rafting and/or flushing may appear to be an effective means of clearing the channel, it is only feasible in areas of deep open water such as Lake George, Lake Munuscong, Potagannissing Bay and Lake Huron. In addition, the distances to the areas where there is sufficient depth and open area to accommodate rafting are greatly in excess of the 100-slab

Table 2. Average distance to rafting sites.

River reach (Figure 1)	*Storage area*	*Average distance* *miles*	*feet*	*meters*
Middle Neebish Channel	Lake George	12	63,360	19,312
Munuscong Channel	Lake Munuscong	10	52,800	16,093
Lake Munuscong Channel	Lake Munuscong	1	5,280	1,609
Lime Island Channel	Potagannissing Bay	5	26,400	8,046
De Tour Passage	Lake Huron	4	21,120	6,427

lengths utilized by Mellor et al. (1978) in their study. Therefore, rafting is limited in its application in the St. Marys River.

CONCLUSIONS AND RECOMMENDATIONS

From the results of this study one can conclude that ice disposal techniques are feasible on the St. Marys River with negligible hydrological impact. A full environmental impact evaluation is beyond the scope of this report, but it is evident that any convenient shoreline deposition of channel ice may well contribute to shore erosion problems and is not recommended at this time.

None of the techniques investigated are feasible on all reaches of the river due to the different hydrological and bathymetric configurations throughout the river system. The technique of mechanical displacement on top of the adjacent ice sheet appears to be feasible throughout the entire system; however, it will result in a 4- to 6-ft (1.2- to 1.8-m) buildup of ice at the edge of the channel. The increase in ice growth due to channel clearing will cause an increase in water velocity of less than 1 ft/s (0.30 m/s) and a water level increase of less than 1 ft (0.30 m), acceptable increases in both areas. A vehicle such as that depicted in Figure 6 could be used to accomplish the clearing. Because a clearing is required every five days, the vehicle must be able to transit the entire system, 40 miles (65 km), in about five days for a clearing rate of approximately 8 miles/day or 0.33 mile/hr for a 24-hour day, or 0.8 mile/hr for a 10-hour day. This can be accomplished by several units stationed in various reaches of the river. Of course, some reaches will not require extensive clearing because they are naturally cleared.

Although clearing by water ejection and slurrying is feasible, it is not recommended at this time because of the projected 40-60% increase in ice accumulation due to freezing of the water used to transport the ice, the necessity of pulverizing the ice, and the problems experienced with the freezing of an ice slurry in the pumps and pipelines.

Rafting or flushing is not feasible in the upper reaches of the river, but they could be used effectively in the lower reaches by rafting the ice into the deep open waters of Potagannissing Bay and Lake Huron.

None of the techniques evaluated will have any significant effect on power generating plants on the St. Marys River. However, there are several warm water discharges that will have an effect on the continuity of the ice sheet at the channel edge. In these areas, the possibility of utilizing an ice boom or ice control structure would have to be investigated. One should also bear in mind that the figures generated above are conservative in nature, i.e. a 50-day ice season was assumed, a 20

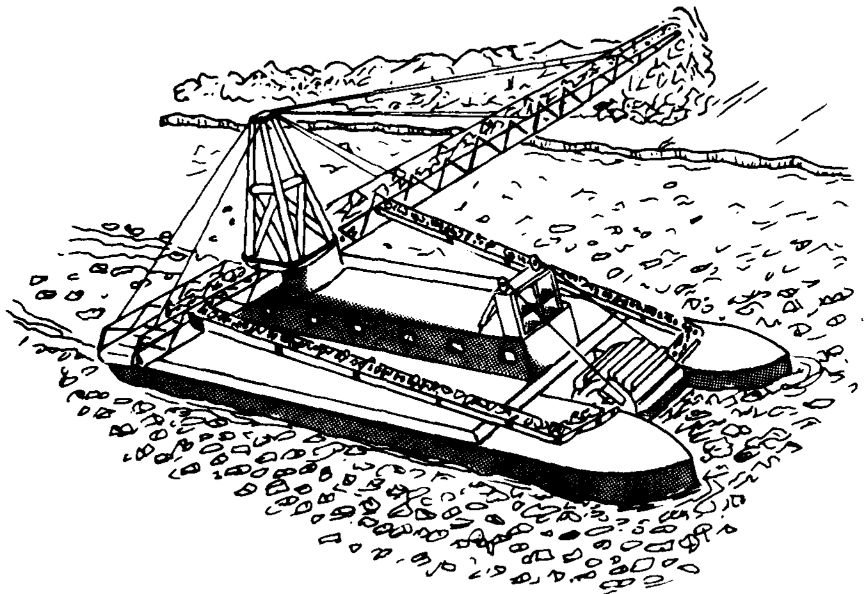


Figure 6. Mechanical disposal on top of the ice by a bucket wheel and boom conveyor system (Arctec Inc. 1979).

freezing degree-day average was utilized, maximum ice growth rates were calculated, no solar melting of disposed ice was allowed for, and therefore, it can be assumed that these figures represent the worst case.

In view of the above, it is recommended that the concept of clearing ice-clogged channels be pursued by:

1. Physically modeling the river reaches under consideration
2. Physically modeling the concept involved
3. Conducting small scale field tests of the concept, utilizing existing dredging equipment as an ad hoc prototype
4. Determining other areas of possible application of the concept, i.e. St. Lawrence Seaway, Upper Mississippi River, Ohio River.
5. Investigating increased roughness and its influence on channel hydraulics.

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